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Experimental investigation of three proton groups and one alpha particle group obtained from deuteron bombardment of N^{14} at low energies

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ABSTRACT

Excitation functions and angular distributions of the three most energetic proton groups from $N^{14}(d,p)N^{15}$ and the ground state group from $N^{14}(d,a)C^{12}$ have been measured for deuterons in the region 500–800 keV. In all the cases studied some resonance structure is obtained at deuteron energies around 700 keV. The anomaly is most pronounced in the angular distributions. In the total cross-section for the ground state protons the available data also seem to give an indication of a small bump at 700-800 keV (corresponding to an excitation of about 21.4 MeV in O^{16}).

Introduction

In the present paper measurements are reported of excitation functions and angular distributions of the three proton groups from $N^{14}(d,p)N^{15}$ leaving N^{15} in the ground state and in the first two excited states at 5.276 and 5.305 MeV [1], and of the ground state alphas from $N^{14}(d,\alpha)C^{12}$. For most of the work two scintillation detectors were used. The separation of the close doublet, however, required magnetic analysis (cf. [2]) and for this a double-focusing analyzer [3] was used. The measurements were performed in conjunction with the Cockcroft–Walton accelerator of the Nobel Institute. Previously, angular distributions of the close proton groups were obtained for 800 keV deuterons [4]. These data, which have partly been remeasured and are included in the present paper, indicated that extended measurements would be desirable. As it is difficult to interpret results of (d,p)-reactions at low deuteron energies, it is necessary to extend such measurements over as wide energy regions as possible.

The ground state group from $N^{14}(d,p)N^{15}$ has been studied at low energies by Jongerius *et al.* [5], Stanley [6], Booth *et al.* [7] and others [1]. The unresolved doublet groups and the ground state group from $N^{14}(d,\alpha)C^{12}$ have also been studied at low energies by several investigators [6], [7], [8]. For measurements at higher energies we refer to [1].

Recently it has been found (see [9], [10] and references in these papers) that the excitation functions of the ground state neutrons from $N^{14}(d,n)O^{15}$ have strong resonance structure containing very broad peaks as well as an indication of fine

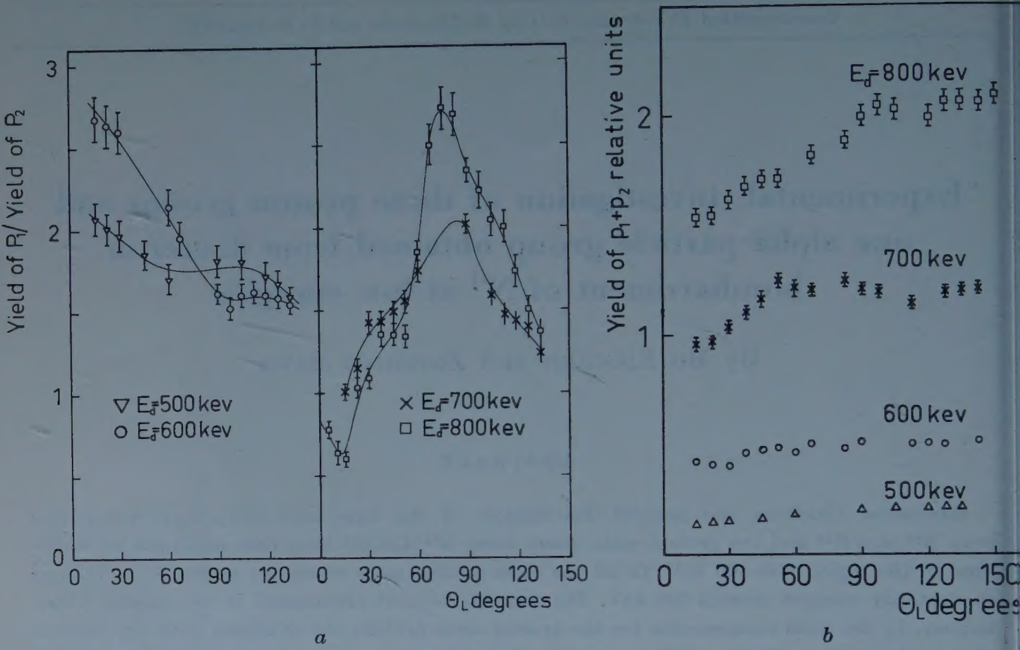


Fig. 1. (*a*) The ratio of the yield of p_1 to the yield of p_2. The errors indicated are the statistical mean deviations and do not include possible uncertainties due to the separation of the two groups. (*b*) The yield of $p_{1,2}$ as a function of laboratory angle with statistical deviations. These are not indicated when being of about the same size as the point.

structure and that the angular distributions vary sharply with the deuteron energy when this is less than 3 MeV. The anomalies observed, however, are for deuterons above about 1 MeV, while the region below this energy was not studied in detail.

Consistent results for the ground state group from $N^{14}(d,n)O^{15}$ were also obtained in [11] for deuterons in the region 1.5–3.0 MeV. In this paper it is also announced that an investigation of the ground state groups from $N^{14}(d,p)N^{15}$ and $N^{14}(d,\alpha)C^{12}$ will be published in the near future.

Experimental procedure

As mentioned above, the equipment used for the study of p_1 and p_2 (i.e. the protons leading to the first and second excited states in N^{15}) included a double-focusing spectrometer with nuclear emulsion plates as the detector. The experimental procedure was the same as has been described in [12]. The targets were produced in the isotope separator of the Nobel Institute by collecting $(N^{14})_2^+$-ions in Al-foils, with a thickness of 0.15 mg/cm^2. These targets, having been exposed to roughly 10 μAh/cm^2 in the separator, gave a somewhat better resolution than the evaporated adenine targets ($C_5N_5H_5$) used previously [4].

In order to obtain measuring points for excitation curves and angular distributions of p_1 and p_2 we used the same procedure as in [4]. We thus measured the yields of $p_1 + p_2$ and also the yield ratios of p_1 to p_2 for different energies and angles.

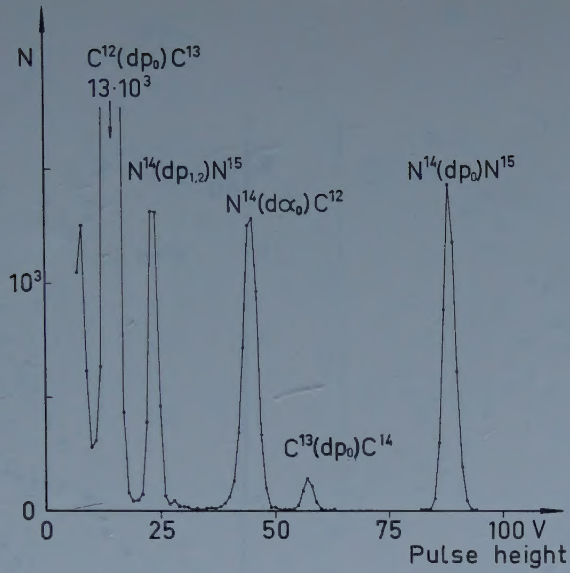


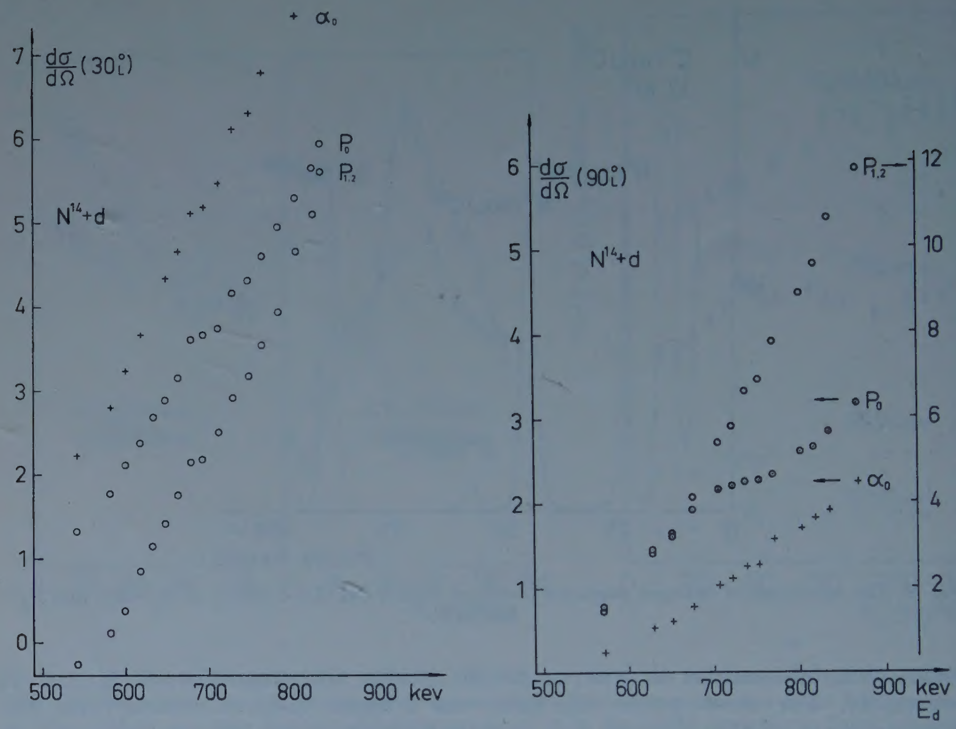
Fig. 2. The spectrum of charged particles obtained with a CsI (Tl)-detector at $\theta_L = 30°$ and $E_d =$ 680 keV.

From this information it was simple to obtain the quantities of p_1 and p_2 separately. For most points the ratio was a mean value of several runs. The measurements of the yield of $p_1 + p_2$ were repeated using the arrangement with scintillation crystals, which will be described in the following. These remeasured yield values agreed in the main with those obtained earlier, but their spread was smaller, partly due to a more accurate current integrator. They were therefore used together with the ratios from the magnetic analysis. The data used for the determination of the angular distributions of p_1 and p_2 are shown in Fig. 1.

In order to investigate the excitation functions and angular distributions of p_0 (the ground state group) we used two scintillation detectors, each consisting of a CsI(Tl)-crystal, 16 mm dia. and 1.5 mm thick, mounted on an RCA 6342 A photomultiplier with a magnetic shield. The scattering chamber was supplied with a number of mylar windows having well defined apertures and corresponding to well defined reaction angles. The detectors were placed outside the chamber and could be rotated around its axis. The charged particles from the target thus reached the crystals after having passed one mylar foil (1.2 mg/cm² thick), about 3 mm air, a light reflector of 0.45 mg/cm² Al-foil and, at forward angles, one 2.75 mg/cm² polystyrene absorber. A detailed description of this arrangement and the scattering chamber will be published later [13].

The pulses from the detectors were amplified and displayed on two 100-channel pulse height analyzers with the same dead time $\leqslant 5 \times 10^{-5}$ sec. An example of a spectrum obtained in this manner is shown in Fig. 2.

The targets used in this part of the investigation was of the "sandwich" type, i.e. a thin adenine layer was evaporated onto an Al-foil, 0.15 mg/cm² thick, and was covered with another layer of Al, 0.05 mg/cm² thick. The adenine thickness was about 10 μg/cm².



a *b*

Fig. 3. Excitation functions: (*a*) p_0, $p_{1,2}$ and α_0 at $\theta_L = 30°$. The yield of the α_0-group is shifted 1 unit upwards and that of the $p_{1,2}$-group 1 unit downwards relative to the yield of the p_0-group. (*b*) p_0, $p_{1,2}$ and α_0 at $\theta_L = 90°$. The ordinate for $p_{1,2}$ is given on the right.

One can see in the spectrum (Fig. 2) the dominant $C^{12}(d,p_0)C^{13}$-peak from the carbon content of the adenine. Nevertheless, it is easy to resolve the peak containing the sum of our p_1 and p_2 groups (p_{12} stands for $p_1 + p_2$) from this carbon peak. This made it possible to remeasure the excitation functions and angular distributions of $p_1 + p_2$, and as mentioned above, these remeasured quantities were used together with the results from the magnetic analysis. As one of the scintillation detectors was used as a monitor in the angular distribution measurements, possible errors caused by the beam integrator, which had been used as a monitor previously, were avoided. Further, we could resolve the $N^{14}(d,\alpha_0)C^{12}$-group in both the excitation and the angular distribution investigations.

The usual care was taken in connection with the excitation function measurements, i.e. an electrostatic supressor of secondary electrons was used, the beam integrator [14] was carefully controlled and the field of the beam analyzing magnet was calibrated with γ-resonances in $F^{19} + p$. The field was measured with sufficient accuracy and reproducibility by means of a Hall detector device. Each excitation function was taken with increasing deuteron energy up to the highest value and then the procedure was repeated with decreasing energy. It should be added that the energies of the incoming deuterons as given in the yield curves in Fig. 3 were corrected for the Allayer in front of the adenine target and for half of the target

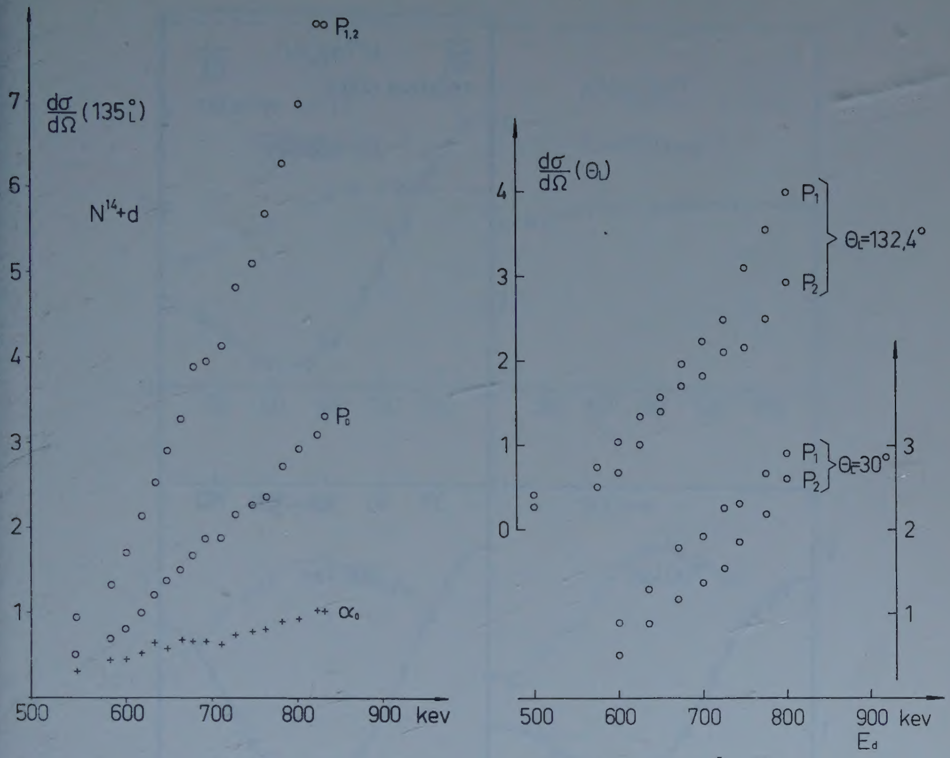


Fig. 3. (*c*) p_0, $p_{1,2}$ and α_0 at $\theta_L = 135°$. (*d*) p_1 and p_2 at $\theta_L = 132.4°$ and at $\theta_L = 30°$ as resolved by magnetic analysis.

thickness. The liquid airtrap was used between the scattering chamber and the rest of the vacuum system.

The energy spread of the deuterons due mainly to the opening of the beam defining slits was about ±8 keV.

The minimum number of counts was at $\theta_L = 135°$

742	for α_0	at 711 keV	
1418	p_0	at 542 keV	
2081	$p_{1,2}$	at 542 keV	

The maximum number was

6679	for α_0	at 639 keV	and 30°
5789	p_0	at 693 keV	and 30°
8340	$p_{1,2}$	at 676 keV	and 90°

These numbers give an idea of the statistics involved in the excitation function investigation as shown in Fig. 3. The yield given there is in relative units, i.e.

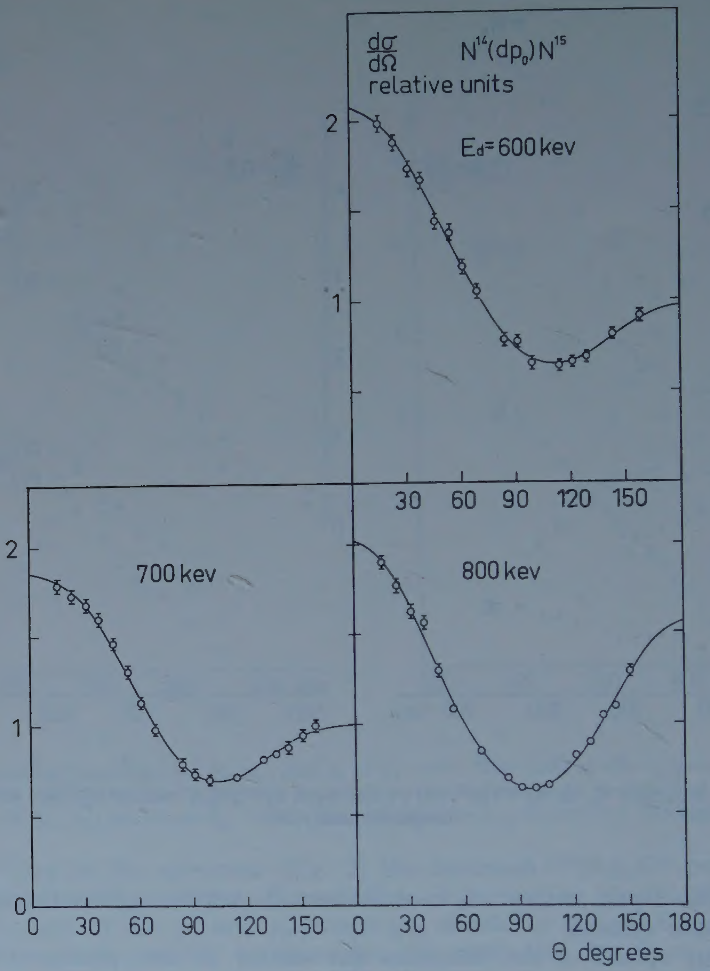


Fig. 4 *a*.

Fig. 4. (*a–d*) Angular distributions of p_0, p_1, p_2 and α_0 for different energies transformed to the centre of mass system. The best fit curves have the form $1+\sum_{i=1}^{4} a_i\, P_i\,(\cos\theta)$ and the differential cross-section $d\sigma/d\Omega$ is obtained by multiplication of this expression by an energy dependent parameter called c (Table 1). In fig. 4 *d* the curves for 700 and 600 keV are shifted upwards 0.5 and 1.0 respectively.

number of counts per 0.2 μC charge and 4×10^{-3} ster. (solid angle subtended by the detector).

In addition, we give in this figure the separated yield for $\theta_L=132.4^\circ$ of p_1 and p_2 as resolved by the double-focusing spectrometer at the Nobel Institute and for $\theta_L=30^\circ$ as resolved by the broad range spectrometer of the University of Bergen.

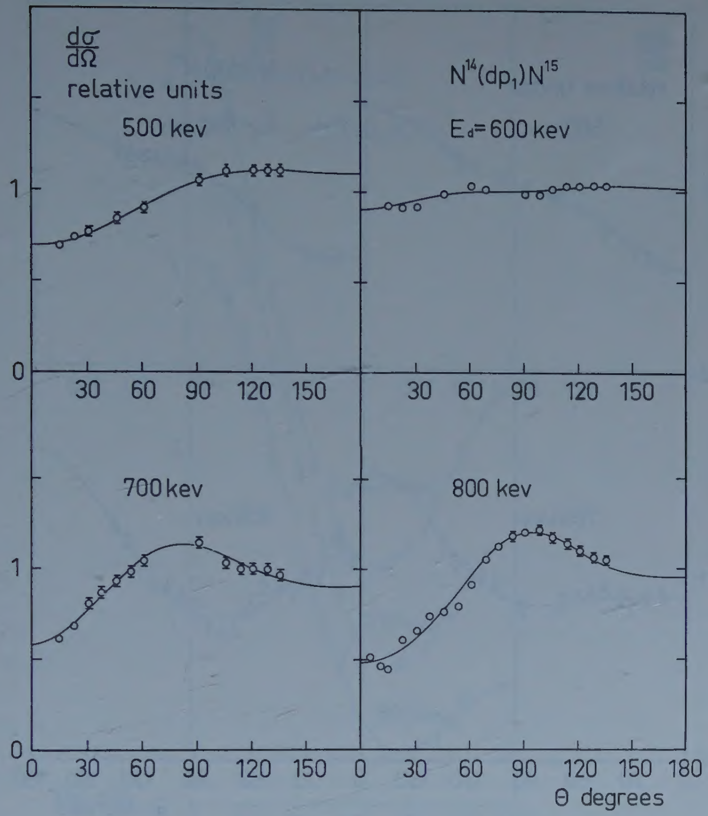


Fig. 4 *b*.

Angular distributions

Measurements of the relative cross-sections were performed at $E_d = 600$, 700 and 800 keV for p_0 and α_0 and at $E_d = 500$, 600, 700 and 800 keV for p_1 and p_2. The angular distributions transformed to the centre of mass system are shown in Fig. 4. To the experimental points a series of Legendre polynomials was fitted according to the method of least squares. In the figures these functions of best fit are indicated. The normalization is such that the constant terms of the series are unity. For the calculation the electronic computor FACIT of the Swedish Board for Computing Machinery was used. The coefficients obtained are collected in Table 1, where the errors indicated are the standard deviations. With a few exceptions coefficients less than or nearly equal to their errors have been omitted.

In Fig. 5, the coefficients a_1 and a_2 from our series of best fit are shown together with values from the literature. It is seen that the results from the different measurements seem to agree fairly well except for the points at about 600 keV where those of Booth *et al.* deviate.

We did not measure the absolute values of the differential cross-sections, but for p_0 these are given by the earlier investigators for some energies. We there-

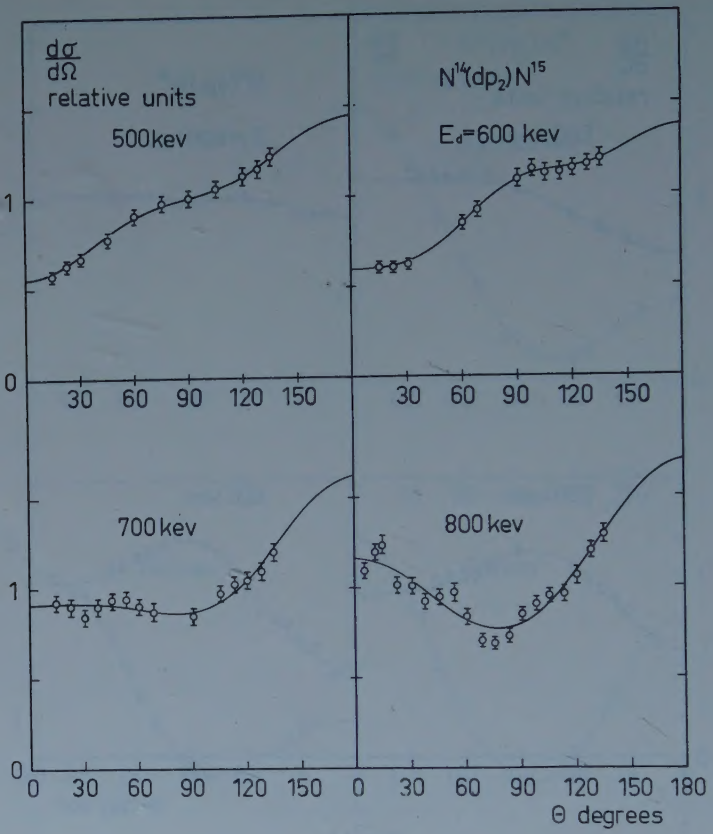


Fig. 4 c.

fore compared our cross-sections with those of Jongerius *et al.* at 600 keV and of Booth *et al.* at 805 keV in order to get the parameter c (see Fig. 4) for the new energies. In each case our cross-section was put equal to the reference value at three points, $\theta = 30^\circ$, 90°, and 135°. The series of best fit were used to represent the angular distributions. We obtained our c at the reference energy by taking the mean of the values corresponding to the three angles. Similarly, by using the excitation functions for the same angles, we computed the c-values at the remaining energies. By comparison with the data of Jongerius *et. al.* at 600 keV the following results were thus obtained for p_0 at 600, 700 and 800 keV, respectively: 0.0725, 0.140, 0.190 mb/ster. From the comparison, in the same way, with the cross-section of Booth *et al.* at 805 keV we had, correspondingly: 0.0749, 0.145, 0.193 mb/ster. The weighed mean values of these pairs of independently determined parameters are indicated in Table 1.

For p_1 and p_2 the c-values were expressed in terms of those of p_0 by means of the yield ratios of $p_{1,2}$ to p_0 and p_1 to p_2 and the best fit series. Also in this case the calculation was performed for the same three angles. At 500 keV, however, for which we did not have the p_0-result, we used the excitation functions

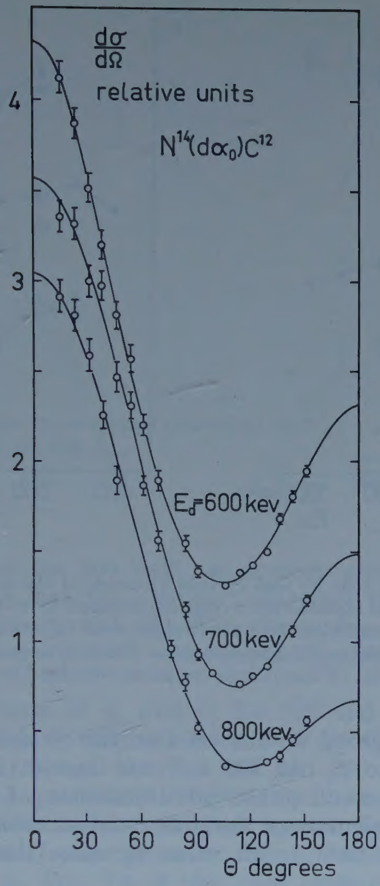
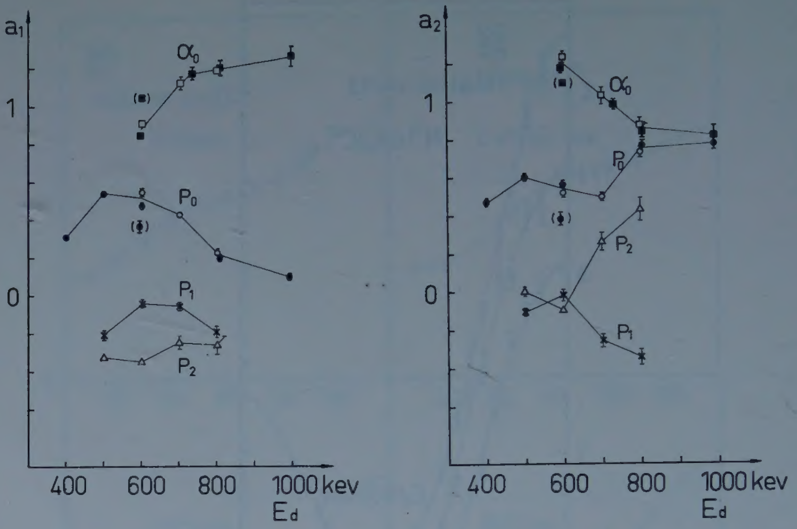


Fig. 4 *d*.

Table 1.

Group	E_d keV	c mb/ster.	a_1	a_2	a_3	a_4
p_0	600	0.075 ± 0.004	0.547 ± 0.016	0.517 ± 0.022	—	—
	700	0.145 ± 0.008	0.429 ± 0.013	0.492 ± 0.017	—	− 0.078 ± 0.016
	800	0.193 ± 0.010	0.228 ± 0.017	0.726 ± 0.025	—	0.047 ± 0.024
p_1	500	0.021 ± 0.003	− 0.208 ± 0.010	− 0.108 ± 0.014	—	—
	600	0.054 ± 0.004	− 0.042 ± 0.021	− 0.017 ± 0.025	− 0.021 ± 0.022	− 0.023 ± 0.045
	700	0.143 ± 0.010	− 0.051 ± 0.017	− 0.252 ± 0.032	− 0.125 ± 0.030	—
	800	0.247 ± 0.017	− 0.190 ± 0.028	− 0.345 ± 0.037	− 0.050 ± 0.037	0.060 ± 0.035
p_2	500	0.013 ± 0.002	− 0.325 ± 0.012	—	− 0.121 ± 0.018	—
	600	0.031 ± 0.003	− 0.346 ± 0.013	− 0.098 ± 0.014	− 0.040 ± 0.013	0.080 ± 0.015
	700	0.090 ± 0.007	− 0.243 ± 0.032	0.261 ± 0.045	− 0.110 ± 0.042	—
	800	0.144 ± 0.011	− 0.262 ± 0.045	0.425 ± 0.059	—	—
α_0	600	0.049 ± 0.004	0.912 ± 0.025	1.229 ± 0.023	0.103 ± 0.025	0.103 ± 0.025
	700	0.095 ± 0.007	1.121 ± 0.035	1.024 ± 0.042	− 0.078 ± 0.046	—
	800	0.145 ± 0.009	1.181 ± 0.032	0.864 ± 0.037	—	—



a *b*

Fig. 5. Coefficients of the P_1 (cos θ) and P_2 (cos θ) terms of the best fit series for the angular distributions. Filled circles and squares show values obtained from the following papers: Jongerius *et al.* (p_0 at $E_d = 400$, 500 and 600 keV), Cartwright *et al.* (α_0 at 595 and 730 keV), Booth *et al.* (p_0 and α_0 at 595, 805 and 990 keV). The results at 595 keV according to Booth *et al.* are put within brackets. The errors of our points are those obtained by the best fit analysis.

at $\theta_L = 132.4°$. For the α-group we also referred the *c*-value to that of p_0 by means of the yield ratio of α_0 to p_0. At 800 keV *c* is thus (0.145 ± 0.009) mb/ster. This can be compared with the result (0.158 ± 0.010)mb/ster. of Booth *et al.* at 805 keV.

It was found in these calculations that the *c*-values obtained at the three angels in no case deviated from their mean value by more than about 5 %.

Discussion

By integration of the best fit curves for $d\sigma/d\Omega$ given in Table 1, the total cross-sections, σ_{tot}, are obtained. These are plotted for the different deuteron energies in Fig 6. Some points taken from other papers are also plotted. It is seen that there seems to be a slight indication of a bump in the excitation function for p_0 at 700–800 keV. We assume that the position of the bump is approximately at 750 keV. There is no clear indication of another irregularity. However, the points are too few to show up a weak anomaly.

The variation of the differential cross-sections with energy, which is shown in Fig. 3, gives fairly good evidence for a slight anomaly in a region around 700 keV. This is most pronounced for p_0 at 90° and for p_2 at 132.4°. However, it is difficult to determine the position of a possible peak, as it seems to vary for different angles. This was also found in ref. [10] for $N^{14}(d,n_0)O^{15}$.

The irregularity of the differential cross-sections for deuterons around 700 keV is demonstrated quite obviously by the angular distributions in Fig. 4, especially for p_1 and p_2. The p_0-curves for 600 and 700 keV deviate from the results re-

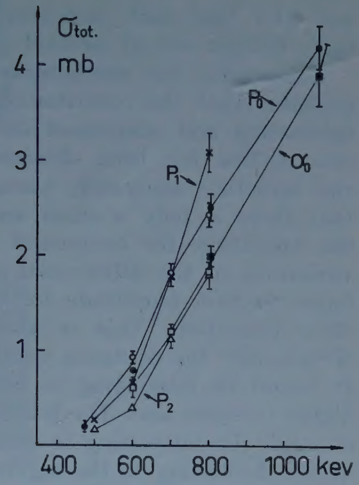


Fig. 6. The total cross-sections for reactions treated in the present paper. For references, see Fig. 5.

ported in [7]. The curve for 600 keV has a more pronounced forward peaking and the one for 700 keV has the "wrong" character in both forward and backward directions as compared with [7]. The curves for α_0 tend to become more unsymmetric with respect to 90° with increasing deuteron energy, which was found also in [7].

The angular distributions of p_1 and p_2 for 500 and 600 keV have the same general behaviour but this is different from that for 700 and 800 keV. The p_2-curves clearly show this change between 600 and 700 keV. The curves suggest an interference process. A quantitative illustration of the above-mentioned properties of the angular distributions is exhibited by the first and second coefficients in the Legendre polynomial expansions in Fig. 5. It can also be noted that the irregularity is apparent in Fig. 2*a* of the yield ratio of p_1 and p_2.

In order to check the large deviation between our result and that of [7] at 600 keV the angular distribution of p_0 at this energy was determined [15] by detecting the particles with nuclear emulsion plates. The result was in good agreement with Fig. 4*a*.

If it is assumed that the compound nucleus O^{16} is formed to some extent in the reactions treated here, it would be excited to about 21.4 MeV, which corresponds to the bump at 750 keV in the total cross-section. Therefore, it would be interesting to look for excited states obtained from the $O^{16}(\gamma,n)O^{15}$ and $O^{16}(\gamma,p)N^{15}$-reactions ([16], [17] and [18], [19]). From $O^{16}(\gamma,n)O^{15}$ several levels [16] have been discovered around 21 MeV, but it is not possible to find a correspondence between our anomaly and any of these, since the absolute energy calibration in the (γ,n)-measurement had an uncertainty of 300 keV. Also the position of our anomaly may have an uncertainty of as much as 100 keV. The states nearest to 21.4 MeV are at 21.21 and 21.52 MeV. The (γ,p)-results indicate no level near this energy.

The investigation of $N^{15}(p,\gamma)O^{16}$ by Cohen *et al.* [20] gives the excitation function at 90° for proton energies corresponding to a region of excitation in O^{16} from about 21 to 26 MeV. These results show two large resonance peaks at 21.8

and 24.7 MeV and, moreover, there is a clear indication of some detailed structure, though not at around 21.4 MeV.

Concerning the mechanism of the reaction $N^{14}(d,p)N^{15}$ at low energies, it is probable that the contribution to the cross-sections from the interference of direct interaction and compound nucleus formation plays an important role. The total cross-section has been obtained for so few energies that it is difficult to estimate the structure accurately enough. However, the present results seem to indicate that there is only a small amount of structure, if any. This might suggest that the amplitude for compound nucleus formation is small. According to this, the variations of the differential cross-sections would be due to interference between a large reaction amplitude for direct reaction and a small one for compound nucleus formation. This is also the conclusion drawn from the investigation of $N^{14}(d,n_0)O^{15}$ for deuteron energies in the much wider region 0.66–5.62 MeV [10]. It would be interesting to have the data for $N^{14}(d,p)N^{15}$ extended to appreciably higher energies also. The total cross-sections should be especially desirable. Finally, it would be interesting to study the proton groups leading to higher excited states in N^{15}. According to the argument of Wilkinson [21], the probability for a stripping process at low deuteron energies can be high if the Q-value is near zero. For these reasons the measurements on $N^{14}(d,p)N^{15}$ are being continued in Bergen by T. Grotdal and the present authors for deuteron energies up to about 1.5 MeV.

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